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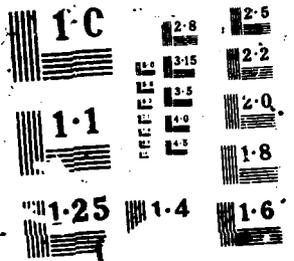
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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

MATERIALS RESEARCH LABORATORY

MELBOURNE, VICTORIA

REPORT

MRL-R-1100

THE VISCOSITY OF MOLTEN TNT

M.A. Parry and H.H. Billon

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THE VISCOSITY OF MOLTEN TNT

M.A. Parry and H.H. Billon

ABSTRACT

The flow behaviour of pure and commercial molten TNT, when subjected to very high rates of shear in the temperature range 82.0 to 95.4°C, is presented. All the data obtained suggest that molten TNT is Newtonian, contrary to some published work, and the temperature dependence of the viscosity of pure TNT is adequately described by an Arrhenius-type relationship of the form $\eta = Ae^{B/T}$ where A = 0.000541, B = 3570 and T is the Kelvin temperature. This equation is characteristic of a simple isotropic liquid. A similar relationship is obtained for commercial TNT. Under some instrumental conditions discontinuities are seen in the shear stress - shear rate flow curves. An analysis of these discontinuities shows them to be caused by the transition from laminar to turbulent flow. Possible implications for processibility and initiation of explosives are discussed.

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CONTENTS

RHEOLOGICAL TERMS USED IN THIS REPORT

The following rheological terms have been used.

Newtonian Flow: A flow regime in which viscosity is independent of applied shear rate.

Dilatancy: An increase in viscosity with increasing shear rate.

Yield Stress: A stress value which must be exceeded (over a practical time scale) before a substance begins to flow.

Thixotropy: Thixotropy is a reduction in viscosity with time of application of shear.

Rheopexy: The opposite of thixotropy, rheopexy is an increase in viscosity with time of application of shear.

Laminar Flow: A flow regime in which the fluid moves in clearly defined layers or laminae.

Streamline: A line following the direction of the fluid in laminar flow.

Turbulent Flow: A flow regime in which the fluid speed at any point varies rapidly in magnitude and direction. Turbulent flow is characterised by the presence of vortices and by the destruction of laminae.

Reynolds Number, R: For the flow of different fluids about geometrically similar bodies, the streamline patterns are similar if the Reynolds number has the same value for each flow. The equation for the Reynolds No. is

$$R = \rho v \ell / \eta \tag{1}$$

where ρ = fluid density, v = flow speed, ℓ = a length characteristic of the geometry and η = fluid viscosity.

Critical Reynolds Number: The Reynolds Number at which the flow undergoes a transition from laminar to turbulent behaviour, and vice versa.

Taylor Vortices: Found in a coaxial cylinder viscometer at the termination of laminar flow behaviour, they are symmetrical, circular and regularly spaced along the length of the cylinder. It is found that neighbouring vortices rotate in opposite senses. The presence of Taylor vortices represents an intermediate phase between laminar and turbulent flow.

Shear Rate in a Coaxial Cylinder Rotational Viscometer: Shear rate can be mathematically defined as,

$$D = 2\omega \frac{R_2^2}{R_2^2 - R_1^2} \tag{2}$$

and

$$\omega = \frac{2\pi \, n}{60} \tag{3}$$

where D is the shear rate, R_1 is the radius of the rotor, R_2 is the radius of the cup, ω is the angular velocity of the rotor and n is the rotational speed of the rotor.

FOREWORD

Unlike most other fields which utilise poured, pumped or extruded products, the explosives area is one in which relatively little research is conducted on material flow behaviour to support manufacture and processing. Yet the range of rheological behaviour is immense - from the low viscosity materials such as nitroglycerine and molten TNT, through the medium viscosity suspensions such as cyclotols (RDX/TNT), octols (HMX/TNT), pentolite (PETN/TNT), and pour-castable polymer bonded explosives, to the more viscous hand-mouldable/extrudable explosives commonly used for demolition and other special purposes. Special mention should also be made of the problems concerned with achieving reliable powder flow of pyrotechnics, primary explosives and high explosives used for pressed compositions. At Materials Research Laboratory we have begun a programme of work to characterise the rheology of new formulations and of compositions of interest to our manufacturing base. This report summarises some of our work concerned with the flow of molten TNT, an important military explosive. TNT melts at 80°C and TNT-based explosive charges are prepared by pour casting methods. In overseas loading plants it is pumped extensively in lagged pipelines.

THE VISCOSITY OF MOLTEN TNT

1. INTRODUCTION

A commonly accepted figure for the viscosity of molten TNT, as cited in the AMCP Handbook [1], is 13.9 mPa.s at $85^{\circ}C$ and 9.5 mPa.s at $100^{\circ}C$. However, Eadie and Milne [2] reported that molten TNT at $83^{\circ}C$ was slightly dilatant (see Fig. 1). Dilatancy describes material flow behaviour where an increase in viscosity is observed as the shear rate is increased. Dilatancy in simple liquids is rare and we thought the phenomenon worthy of further study.

May, Thorpe and Connick [3] reported that TNT could form a glass after thermal cycling. They melted small samples of pure TNT by heating them to $90^{\circ}C$ and then cooled them to solidification in a differential scanning calorimeter (DSC), and found that repeated temperature cycling caused the nucleation temperature to drop, until eventually, a glass formed. They suggested that potential crystallisation nuclei were being destroyed by successive temperature cycles. We inferred from their work that it may be possible for TNT to retain a high degree of order in the molten phase, and not behave as a completely isotropic liquid until it has been temperature cycled, and that this might serve as a basis for the explanation of its reported non-Newtonian flow behaviour.

In contrast Moore, Burkardt and McEwan [4] measured the viscosity of molten and supercooled molten TNT with a modified Ostwald (Cannon-Fenske) capillary viscometer and found no evidence for non-Newtonian flow. They found that the temperature dependence of viscosity of TNT was best represented by a continuous exponential function of the type,

$$\log \eta = A + B/T + C/T^2 \tag{4}$$

where η was the viscosity in cP, T was the temperature in degrees Kelvin and A, B and C were constants. For TNT, A = 2.78, B = - 2810 and C = 7.8 x 10^5. However, the

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design of gravity force capillary viscometers such as the Cannon-Fenske type do not give rise to a defined shear rate and are therefore not suited for the study of non-Newtonian behaviour [5]. Unfortunately Moore et al. were unable to state the shear rate range over which they investigated.

2. PROCESSING AND INITIATION OF TNT

There are two important reasons for investigating dilatancy (and turbulence) in molten TNT; these are related to its processibility and initiation. Investigations were conducted at shear rates up to and beyond those studied by previous workers.

2.1 Processibility

Dilatant substances increase their viscosity whenever shear rates increase. In other words, the faster one tries to pump molten TNT in the loading plant (for higher throughput of ordnance), the more viscous the TNT may become. Dilatant materials have been known to stop flowing in a pipeline after the shear rate (flow) was increased and have the potential to burn out the motors on pumps.

2.2 Initiation

As a result of an investigation into the safety and serviceability of the HARPOON missile after aerodynamic heating when carried aboard the F111C aircraft [6], we have begun work on the impact initiation of liquid explosives. More recently, we have been asked to comment on potential hazards of firing ammunition from a hot gun which may have partially melted the explosive filling prior to gun firing [7]. Molten TNT is thought to be very impact sensitive [8]. One mechanism which has been proposed to account for the sensitiveness of liquid explosives during impact is that of viscous heating [9]. Early workers had shown that the impact sensitiveness of nitroglycerine (NG) was greatly enhanced by the presence of gas bubbles which were rapidly compressed during impact to produce hotspots [10]. Ignition occurred at random positions in the sample. However, when bubble-free NG was seen to ignite at the rapidly-flowing NG periphery during impact, this was evidence for a viscous heating mechanism, since it was at the periphery that there was maximum rate of shear [11]. A number of workers [12-14] have calculated that high temperatures could occur at the periphery of liquid explosives by rapid flow between two impacting anvils according to,

$$\frac{\delta T}{\delta t} = \frac{\eta}{\rho C} \frac{\delta V_r}{\delta Z}^2 \tag{5}$$

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where, η is the viscosity, ρ is density, C is specific heat, V_r is radial flow and z is the vertical axis where flow is laminar. Further,

$$\frac{\delta V_r}{\delta z} = \frac{4V_r}{h}$$ (6)

where $\delta V_r / \delta z$ is the maximum shear rate, V_r is the radial flow, h is the film thickness; it is assumed that no heat is lost to the anvils. Others have proposed that impact initiation of solid explosives occurred by viscous flow of tiny quantities of molten material between grains of explosive or at the anvil surface [15]. It was proposed that interparticle friction caused molten material to form during the early stages of impact and that a subsequent, localised, rapid temperature rise occurred which was associated with rapid flow through 'hypothetical capillaries' given by Poiseuille's equation for laminar flow,

$$\Theta = 8\ell\eta V / a^2 \rho C$$ (7)

where Θ is the calculated temperature rise for a liquid of viscosity η, density ρ, and specific heat C, flowing through a capillary of length ℓ and radius a, with an average velocity V.

More recently, Frey [16] combined various heating mechanisms which he proposed could possibly occur in the vicinity of a collapsing cavity into one model in an attempt to determine the conditions under which each was dominant. Over a range of pressurisation rates he found that viscoplastic work was by far the most efficient mechanism for producing high temperatures and that it was favoured by high viscosity, low yield strength and short rise times. For shock waves, where the rise time was very short, viscous heating was dominant, and high temperatures were expected.

The possibility of dilatancy in TNT is important since during impact and shock loading of explosives the shear rate will necessarily be high and the temperature rise is proportional to the viscosity of the material undergoing viscous flow. Dilatancy consequently offers a possible explanation for the ease of initiation of molten TNT which has not been considered previously.

2.3 Turbulent Flow

The viscometer is designed to assess laminar flow behaviour. It is known that liquids of low viscosity can give rise to curvature or a break in the shear rate shear stress flow curve due to turbulent flow. Turbulent flow requires a much higher energy to be maintained than laminar flow. This work also sought to identify if turbulent flow could occur in molten TNT at 'practical' shear rates. Turbulence would have implications for processibility and initiation of TNT.

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3. EXPERIMENTAL

3.1 Materials and Sample Preparation

Two grades of TNT were investigated; commercial grade with a set point 80.2°C (lot MDK 469) and ultra pure TNT, purified according to Ref.[17]. The purified TNT showed no detectable impurities when analysed by GLC. The TNT was prepared for rheological examination by melting in a jacketed kettle which was maintained at 95°C, the same temperature as the viscometer temperature vessel. The rotor and cup were maintained in an oven at 95-100°C for at least an hour prior to use, then were transferred to the viscometer. The cup was filled with molten TNT from the kettle, the rotor was screwed on to the measuring head, the cup was inserted in the viscometer temperature vessel and the cup/temperature vessel were then fixed to the viscometer in the configuration shown in Fig. 2. The temperature was then programmed down to 82.0°C (the lowest test temperature) and the sample was allowed to equilibrate for 1 hour. Any excess sample was then removed from the cup/rotor sensor system by using a heated Pasteur pipette. The sample was again allowed to equilibrate whereupon a measurement was conducted. Measurements were then taken at successively higher temperatures up to 95.4°C. This technique was designed to prevent any sample contraction errors; starting at a higher temperature could have led to an unfilled cup at lower temperatures and provided an error in the measurement. It was considered necessary to slightly underfill the cup when using the MV DIN and MV II rotors (see Fig. 3) in order to prevent freezing of TNT at low test temperatures.

3.2 Apparatus Description

All viscosity measurements were conducted on a Haake RV 2 viscometer (see Figs 2 and 3) where the test sample is placed in a cylindrical cup, shear is applied to the sample by rotation of a cylindrical rotor, coaxial with the cup, and rotor/sample cup are surrounded by a temperature vessel. The temperature vessel was linked in series with a jacketed kettle and a Haake N3 temperature-controlled bath, with the circulating fluid being distilled water. The shear rate of the sample depends on the radii of the cup and rotor as well as the rotor speed (see equns (2) and (3)). The shear stress was measured by means of a torque measuring head which connected the rotor to a drive unit. The drive unit and measuring head were electrically connected to an RV 2 "basic unit" which, in turn, was connected to a PG 142 shear rate programmer and to a Hewlett Packard X-Y-T recorder. The value of torque (shear stress) indicated was accurate to 1 scale division in 100 of chart. The NV sensor system was calibrated using standard fluids. For extended shear experiments an Omniscribe strip-chart recorder was substituted for the X-Y-T recorder.

The temperature of the samples for the MV DIN and MV II experiments was measured both by means of a Mettler TM 102 platinum-resistance thermometer which was suspended in the N3 bath and also by a type 'T' thermocouple which was immersed in a glycerol-filled recess in the viscometer temperature vessel. The TM 102 platinum-resistance thermometer and the type 'T' thermocouple were both readable to 0.1°C and had the same uncertainty of calibration of 0.2°C to a confidence level of 99 percent. More accurate sample temperatures for the NV experiments were measured by means of a Guildline 9540 platinum-resistance thermometer. TNT was melted in a cup jacketed

vessel combination, then the bath was programmed to a pre-determined temperature in the range 81.5 to 95.0°C, (nominal temperatures only), the temperature was then varied in half-degree increments. Both the temperature in the TNT and in the viscometer water jacket were then measured using a 3 mm diameter probe with the Guildline platinum-resistance thermometer. By this process it was possible to correlate the temperature of the TNT with the temperature of the jacketed vessel and thus to convert temperature readings taken within the jacketed vessel of the NV sensor system to an actual temperature for the TNT. The Guildline unit was readable to 0.001°C and had an uncertainty of calibration of less than 0.05°C to a confidence level of 99 percent. In all cases temperature measurements were appropriately corrected by interpolation using calibration tables supplied by a NATA authority. The maximum drift in the programmed temperature of the N3 bath was 0.01°C, which was well within the uncertainty limits of all the thermometers used.

Experiments were conducted using an MV DIN and MV II rotor with an MV cup and an NV rotor/cup system (see Fig. 3). The MV II rotor had a cylindrical shearing surface. The MV DIN rotor had a conical, as well as a cylindrical, shearing surface, whereas the NV rotor sheared the sample on the inner and outer surfaces of a cylinder. The temperature in the inner gap of the NV system was controlled by a second, internal, temperature vessel. The sizes of the annular gap between rotor and cup were 1.64 mm, 2.6 mm and 0.35 mm or 0.40 mm for the MV DIN, MV II and NV systems respectively. The shear rate ranges used in this investigation for each of the sensor systems was as follows: MV DIN 0-840 s^{-1}, MV II 0-270 s^{-1} and NV 0-5300 s^{-1}.

When molten TNT was sheared to very high shear rates, the apparatus was enclosed in an explosion-proof fume cupboard designed to prevent injury to the operator in the event of an explosion.

4. RESULTS AND DISCUSSION

Two types of experiments were performed. The first involved shearing the sample over a range of continuously variable shear rates from rest to the maximum desired shear rate and back to rest, and recording the consequent torque (shear stress) as a function of shear rate. These results are presented as flow curves at a range of temperatures. The second type of experiment involved shearing the sample at a constant shear rate for a specified period of time and measuring the consequent torque (viscosity) as a function of time.

Figure 4 is an example of the flow curve produced when commercial grade TNT at 95.4°C was sheared from rest to 5300 s^{-1} (the maximum shear rate achievable with our equipment). Clearly, TNT exhibits a linear relationship between shear rate and shear stress and so the sample shows Newtonian flow behaviour at this temperature. Figure 5 is a further illustration of the constant viscosity behaviour of TNT at 95.4°C. Commercial TNT was sheared at 490 s^{-1} for 6 hours and the viscosity remained unchanged (within an experimental uncertainty of shear stress of about 0.2 Pa).

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Eadie and Milne [2] conducted their work at 83°C using rotation speeds below 400 rpm (shear rates below 586 s^{-1}). We therefore produced flow curves of both pure and commercial TNT over the temperature range 82.0°C to 95.4°C in approximately 0.5°C increments, over the shear rate range 0 - 1250 s^{-1}. Figures 6 and 7 show examples of the flow curves produced at 82.0°C, 85.4°C and 95.4°C. Once again, strictly Newtonian flow was observed and it is justifiable to attribute one value to the coefficient of viscosity of molten TNT at constant temperature. A slight, but observable difference in viscosity was obtained for pure and commercial materials; commercial TNT was slightly less viscous. Figure 8 shows the plots of log viscosity as a function of reciprocal temperature and illustrates this difference. The formulae derived from Fig. 8, relating log viscosity and reciprocal temperature, were linear, with correlation coefficients of 0.998 for pure TNT and 0.996 for commercial TNT. Slightly better correlation could be obtained for commercial TNT using a cubic or quadratic fit. The temperature dependence of the viscosity η of TNT, over the range 82.0 to 95.4°C, can therefore be adequately described by an Arrhenius-type relationship of the form

$$\eta = Ae^{B/T} \tag{8}$$

where A = 0.000346, B = 3720 for commercial TNT and A = 0.000541, B = 3570 for pure TNT, and T is the Kelvin temperature.

An equation of this type has been found to describe the behaviour of many simple liquids because the liquid may be viewed as having a disordered, and consequently isotropic, lattice structure which possesses vacant lattice sites or 'holes'. Deformation and flow takes place by the motion of molecules into the holes. The work required to form a hole and to move a molecule into it determines the flow activation energy, thus there is an analogy with the potential barrier which must be overcome before two molecules will react chemically and this accounts for the resemblance of equation (8) to the equation for chemical reaction rates.

Unlike Moore et al. [4] we find no reason to postulate an inverse temperature dependence of the flow activation energy over the temperature range examined and consequently the second order terms stated earlier in equation (4) are considered unnecessary. Presumably, we do not require a second order term because our temperature range investigated was small (13.4°C), the temperatures of the molten TNT were only measured to an accuracy of 0.05°C, and the η to an accuracy of ± 0.4 mPa.s. As a result, no changes were observed in the flow activation energy over this range. Although the Moore et al. [4] analysis indicated that the root-mean-square (rms) deviation from a linear form of log η for TNT over the temperature range they investigated, of 33°C, was very small, it was more than an order of magnitude greater than the rms deviation from a quadratic fit.

Eadie and Milne [2] used a rotational viscometer which had a relatively large annular gap for their TNT work. We therefore attempted to produce apparent dilatancy using our viscometer with the MV DIN and MV II rotors which had larger gap sizes than the NV rotor; we had used the NV rotor to clearly demonstrate Newtonian flow behaviour in TNT. Flow curves of TNT were produced over the temperature range 82°C to 95°C in approximately 1°C increments, over the shear rate ranges 0-840 s^{-1} (for the MV DIN) and 0-270 s^{-1} (for the MV II). Examples of flow curves produced at 82°C, 85°C and 95°C for

both sensor systems are shown in Figs 9 and 10. It is seen that all flow curves exhibit a discontinuity or "knee" which occurs at lower shear rates for experiments conducted at higher temperatures (lower viscosities). To investigate if the cause of these discontinuities was related to the transition from laminar to turbulent (or vortical) flow we plotted the product $n\rho/\eta$ (which is proportional to the Reynolds Number for a given sensor system), obtained at the discontinuities, against the temperature (n is the observed rpm at the transition point, ρ is the density and η is the viscosity). Figure 11 shows that the products are constant, within the uncertainty limits represented by the error bars. A detailed theoretical analysis of the stability conditions for the flow between two coaxial cylinders has been conducted by Taylor for the special case where the annular gap is small compared to the mean value of the inner and outer radius [18] and an exact analysis has also been completed by Chandrasekhar [19]. The analysis by Taylor includes a formula for a critical angular velocity (Ω_c), where

$$\Omega_c^2 = \frac{\pi^4 \nu^2 (R_1 + R_2)}{2Ps^3 R_1^2}$$

(9)

and ν is the kinematic viscosity, R_1 is the inner radius, R_2 is the outer radius, the annular gap $s = R_2 - R_1$, and P is given by the following formula,

$$P = 0.0571 [1 - 0.652 (s/R_1)] + 0.00056 [1 - 0.652 (s/R_1)]^{-1}$$

(10)

The critical rpm values for the MV DIN and MV II sensor systems determined by analysing the observed flow curve discontinuities and by calculation according to Taylor's formula are tabulated in Tables 1 and 2.

The products plotted in Fig. 11 are proportional to the Reynolds Numbers for the flows in the MV DIN and MV II systems; as a consequence, they are constant for a given streamline configuration. The fact that they were found to be constant in this case, at the discontinuities of the flow curves, indicates that the same streamline configuration was attained at the point of occurrence of the discontinuities for each sensor system. Since we may assume that the geometrical configuration of a sensor system is unchanged over the temperature range considered, it would be expected that the same streamline configuration would occur before the transition from laminar flow no matter what the temperature, viscosity or density of the fluid under consideration. This information, coupled with the fact that there is reasonable agreement between the observed and predicted critical rpm values (Tables 1 and 2), implies that the discontinuities represent a point of transition from laminar to turbulent flow. (To be precise, the transition is to vortical flow, since the presence of regularity in this mode of flow precludes the strict use of the term turbulent).

Jerrard [20] has stated that external disturbances such as system vibrations can cause an earlier departure from laminar flow than that predicted by equation (9) since the criteria for turbulence given by Taylor and used to derive equation (9) are only completely valid when turbulence is solely the result of inertial forces. However our results do not indicate observed critical rpm values lying consistently below the predicted values. This is presumably due to the estimated uncertainty of 10 rpm in

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determining the observed critical rpm values as well as to the uncertainty in the predicted critical rpm values which was estimated at 6 rpm and 12 rpm for the MV II and MV DIN sensor systems respectively.

It is of interest to apply equation (9) to the system used by Eadie and Milne [2]. In their determination of the viscosity of TNT at 83°C, they used a coaxial cylinder rotational viscometer with R_1 = 25.33 mm, R_2 = 27.362 mm, and consequently s = 2.032 mm. This leads to a P value of 0.055 (from eqn (10)) and a critical rotation speed of 232 rpm (from eqn (9)). Their results were quoted over a rotation speed range of 0 rpm to about 350 rpm (see Fig. 1) and consequently some turbulence would have been present in their system during viscosity measurements. A transition point would have been difficult to detect because of the pointwise plotting of data. It is now clear that their reported increase in observed viscosity with increasing shear rate was a consequence of turbulence and was not the result of dilatancy in the flow behaviour of TNT.

We also obtained flow curves exhibiting a transition from laminar flow for distilled water with the NV system (not shown). By finding the appropriate product (as in Fig. 11) we have estimated that the onset of vortical flow of TNT at 100°C would occur at 1922 rpm (10,148 s^{-1}) on the NV system and that a discontinuity would appear at 999.9 rpm (the maximum rotation speed of the NV system) if the molten TNT was heated to 128°C.

These results have implications for the processing and initiation of TNT. During pumping of molten TNT the flow will become turbulent if the flow rate (shear rate) is too high. In a similar manner to dilatancy, this has the potential to "burn-out" pump motors or could lead to increased power costs. We have predicted that even very thin films of molten TNT (as in the NV sensor system) can undergo transition from laminar flow to turbulence. The rate of shear of explosives such as molten TNT or exudates [6] during processes which involve shock loading, impact loading and gun firing of ordnance will be very high. We believe that during these processes turbulence may act in a similar manner to dilatancy, it could lead to hot spots of high localised temperatures in molten TNT during rapid flow. This factor must be considered during the modelling of initiation processes, during accident investigations and for studies into mechanisms of the impact and shock initiation of molten TNT and other liquid and paste explosives.

Application of this work to initiation processes is still not resolved. The transition to tubulence was studied under steady state conditions, but initiation occurs under transient conditions. The transient response of TNT may, or may not, be simply related to the steady state response, as the vortices may take a finite time to develop. Furthermore, since most initiation phenomena in explosives are concerned with processes leading to relatively short applications of high pressures it is important to establish the pressure dependence of viscosity. For example, Tanner [21] has noted that the viscosity η is given by,

$$\eta = \eta_0 \, e^{\rho / \beta} \qquad (11)$$

where η_0 is the viscosity at zero pressure, ρ is the pressure and β is the pressure-viscosity exponent. Tanner [21] also noted that mineral oils typically have a value of β in the range 30-50 MPa, while common polymers typically have a value of β in the range 20-80 MPa. If explosives show similar pressure-viscosity exponents it can be seen that

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high pressures will probably lead to large increases in the viscosity of molten TNT. The pressure-viscosity exponent for molten TNT should be established.

5. CONCLUSIONS AND RECOMMENDATIONS

The flow behaviour of pure and commercial molten TNT in the temperature range 82.0-95.4°C was strictly Newtonian, contrary to some other published work. The temperature dependence of the viscosity was adequately described by an Arrhenius-type relationship, which is characteristic of an isotropic liquid. A range of instrumental conditions were employed to demonstrate how the onset of turbulence can be misinterpreted as dilatancy. In film sizes of millimetre dimensions molten TNT will transit from laminar flow to vortical flow at moderate shear rates. The onset of turbulence has implications for pumping of molten TNT in the loading plant. Furthermore, during initiation, a mechanism which involves the transition from laminar flow to turbulence may give rise to hot spot temperatures previously considered to be unattainable by this process.

It is recommended that the pressure dependence of the viscosity of molten TNT be investigated.

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TABLE 1

Predicted and Observed Critical RPM Values for MV DIN System

Temperature (°C)	n_{cp} (rpm)	n_{co} (rpm)	Deviation (rpm)	Percent Deviation
82.4	397	398	1	0.3
83.4	379	371	8	2.2
84.4	369	376	7	1.9
85.4	361	360	1	0.3
86.3	352	348	4	1.1
87.3	343	336	7	2.1
88.4	334	334	0	0.0
89.4	325	324	1	0.3
90.5	316	316	0	0.0
91.6	307	311	4	1.3
92.5	297	300	3	1.0
93.6	288	296	8	2.7
94.6	288	281	7	2.5
95.4	279	278	1	0.4

Average percent deviation: 1.2%
Average deviation: 4 rpm
n_{cp} was predicted from Taylor's equation (Refs [18,20])

Explanation of symbols:

n_{cp} = Predicted critical rpm value

n_{co} = Observed critical rpm value

Deviation = $|n_{cp} - n_{co}|$

Percent Deviation = $(|n_{cp} - n_{co}| / n_{co}) \times 100$

TABLE 2

Predicted and Observed Critical RPM Values for MV II System

Temperature ($^{\circ}$C)	n_{cp} (rpm)	n_{co} (rpm)	Deviation (rpm)	Percent Deviation
82.4	211	218	7	3.2
83.4	201	212	11	5.2
84.4	196	205	9	4.4
85.4	192	198	6	3.0
86.3	187	191	4	2.1
87.3	182	184	2	1.1
88.4	177	180	3	1.7
89.4	173	169	4	2.4
90.5	168	167	1	0.6
91.6	163	157	6	3.8
92.5	158	159	1	0.6
93.6	153	154	1	0.6
94.6	153	151	2	1.3
95.4	148	147	1	0.7

Average percentage deviation: 2.2%
Average deviation: 4 rpm
n_{cp} was predicted from Taylor's equation (Refs[18,20])

Explanation of symbols:

n_{cp} = Predicted critical rpm value

n_{co} = Observed critical rpm value

Deviation = $|n_{cp} - n_{co}|$

Percent Deviation = $(|n_{cp} - n_{co}| / n_{co}) \times 100$
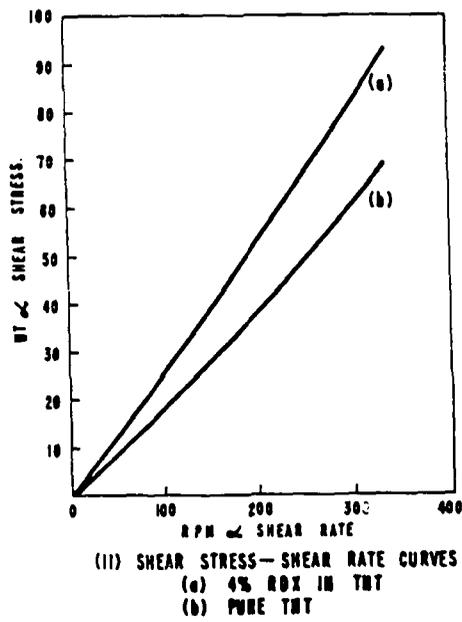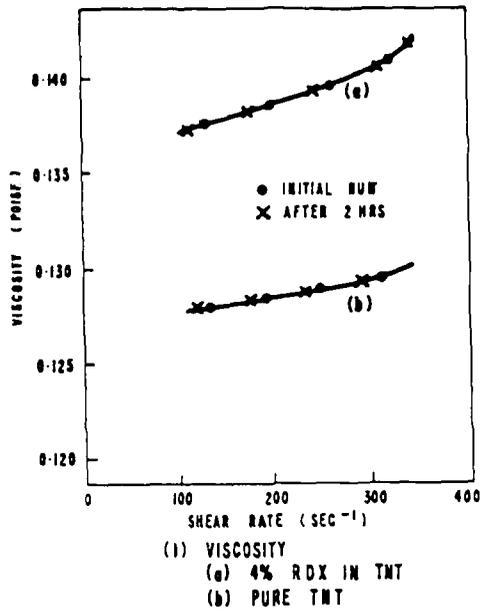
FIGURE 1   Results of Eadie and Milne (from Ref.[2]) showing apparent dilatancy for both pure TNT and 4% RDX in TNT at 83°C.
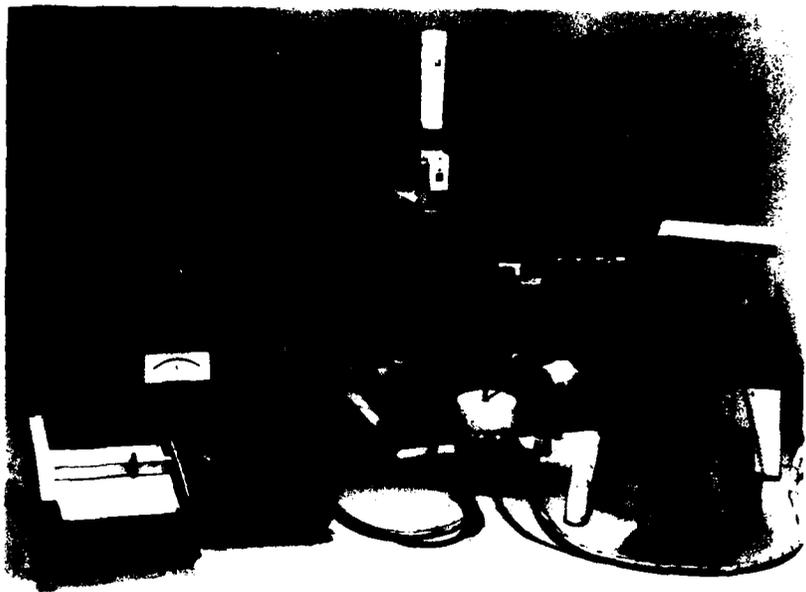
FIGURE 2   Experimental arrangement used in TNT viscosity determinations (Guildline digital thermometer not shown).
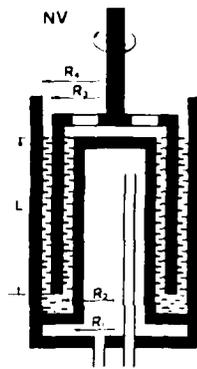
a) NV cup and rotor.
$R_1 = 17.5$ mm;
$R_2 = 17.85$ mm;
$R_3 = 20.1$ mm ;
$R_4 = 20.5$ mm
Maximum viscosity range
2-10^4 mPa.s
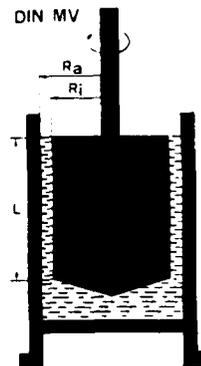
b) MV DIN cup and rotor.
$R_i = R_1 = 19.36$ mm
$R_a = R_2 = 21$ mm
Gap = 1.64 mm
Maximum viscosity range
10-10^5 mPa.s
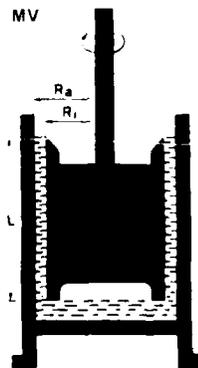
c) MV II cup and rotor.
$R_i = R_1 = 18.4$ mm
$R_a = R_2 = 21$ mm
Gap = 2.6 mm
Maximum viscosity range
50-10^6 mPa.s

FIGURE 3   Dimensions and maximum viscosity ranges of the sensor systems used.
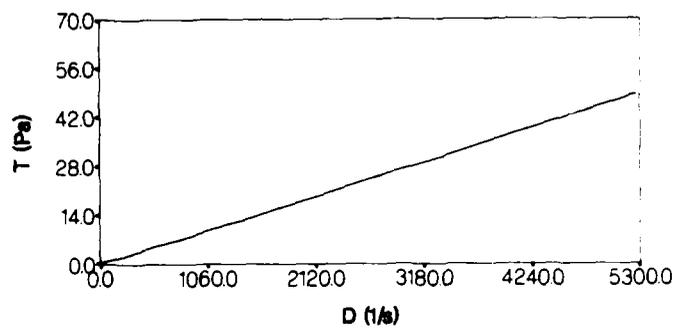
FIGURE 4   Flow curve of commercial grade TNT at 95.4°C, using NV system over a shear rate range of 0-5300 s⁻¹.
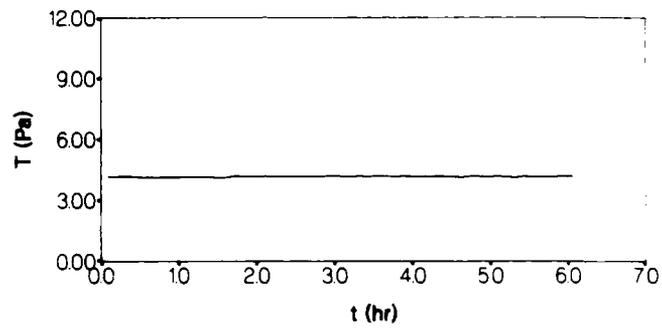
FIGURE 5   Viscosity of commercial grade TNT at 95.4°C with constant shear of 490 s^{-1}, for 6 hours, using NV sensor system.
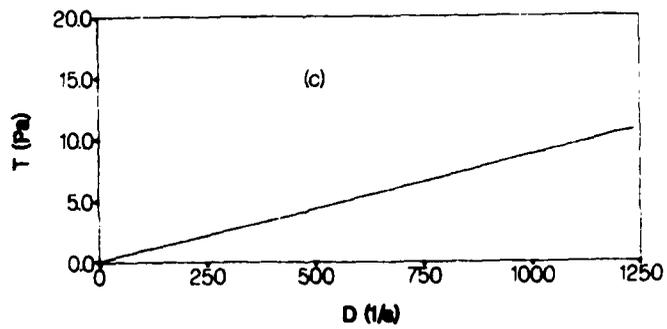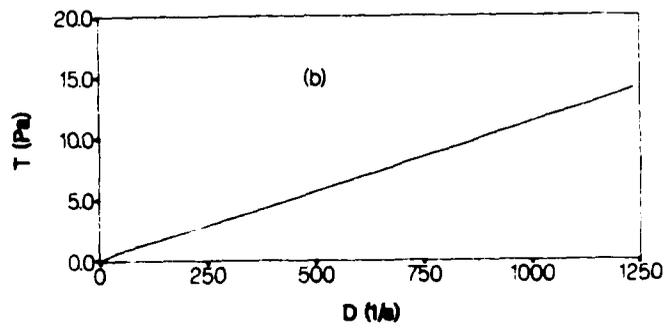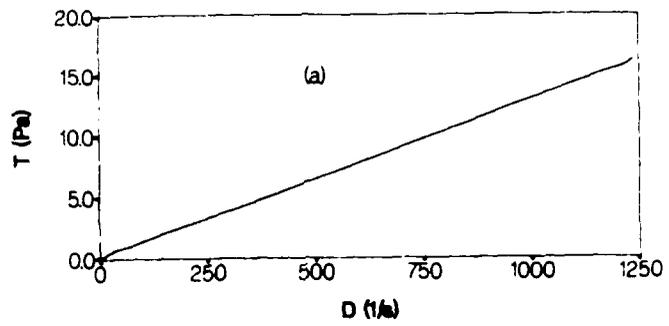
FIGURE 6   Flow curves of pure TNT at (a) 82.0°C, (b) 85.4°C and (c) 95.4°C, using
NV sensor system over a shear rate range of 0-1250 s⁻¹.
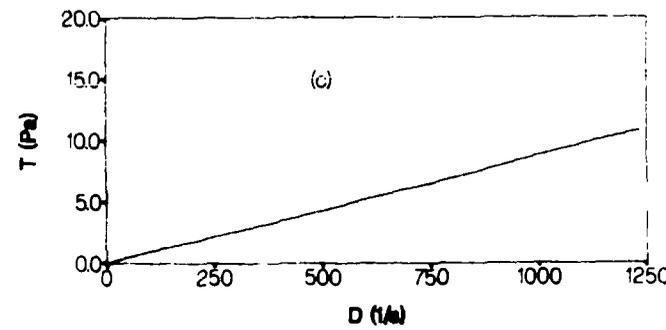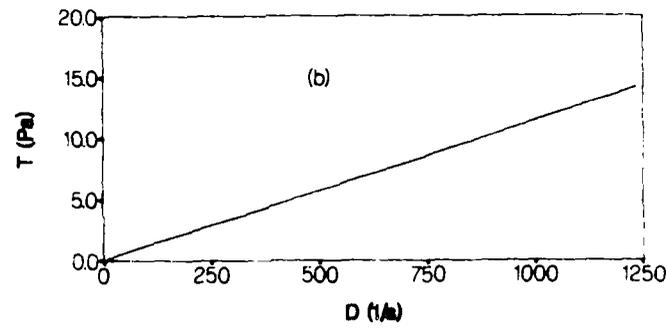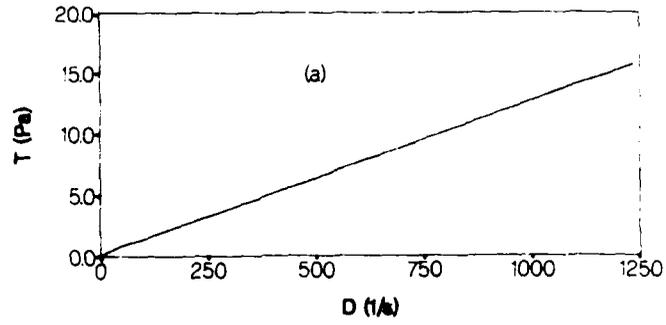
FIGURE 7   Flow curves of commercial grade TNT at (a) 82.0°C (b) 85.4°C and (c) 95.4°C, using NV sensor system over a shear rate range of 0 - 1250 s⁻¹
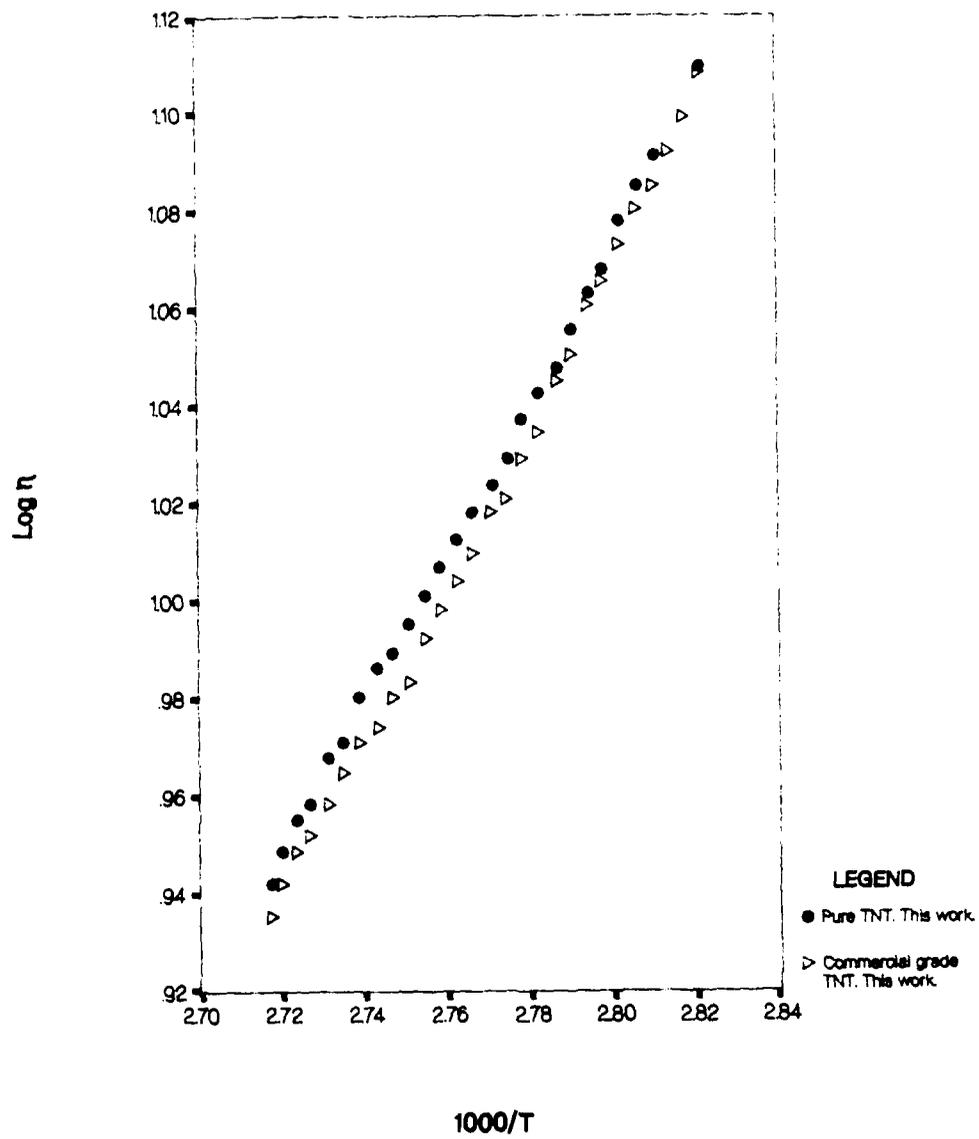
FIGURE 8   Plots of log viscosity versus 1000/T for pure and commercial grade TNT.
Data obtained using HAAKE RV2 Viscometer with NV sensor system.
(Viscosity in mPa.s and T in degrees Kelvin).
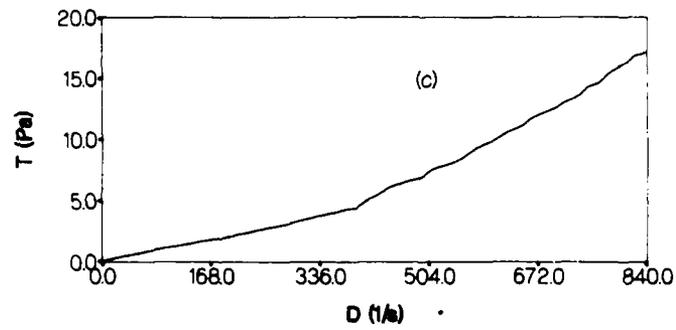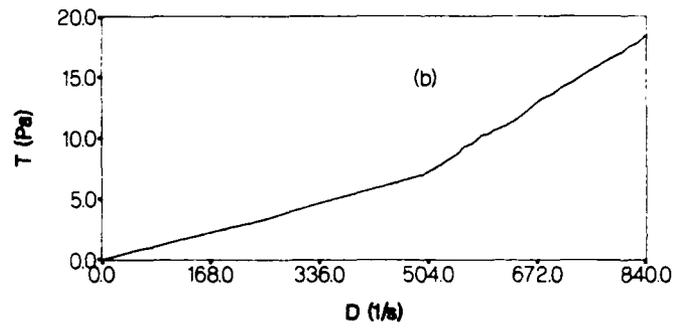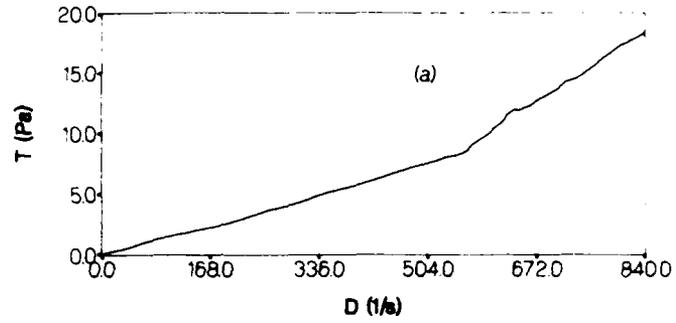
FIGURE 9   Flow curves of commercial grade TNT (exhibiting discontinuity) at (a) 82°C, (b) 85°C and (c) 95°C, using MV DIN sensor system over a shear rate range of 0-840 s^{-1}.
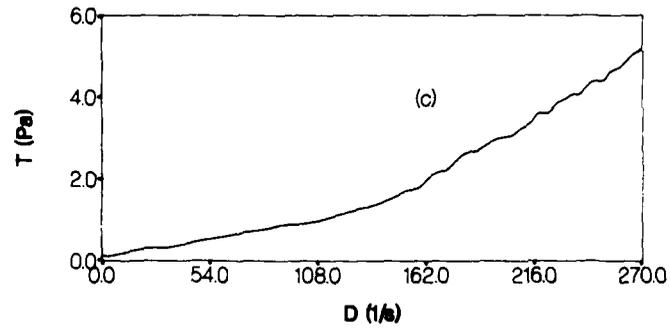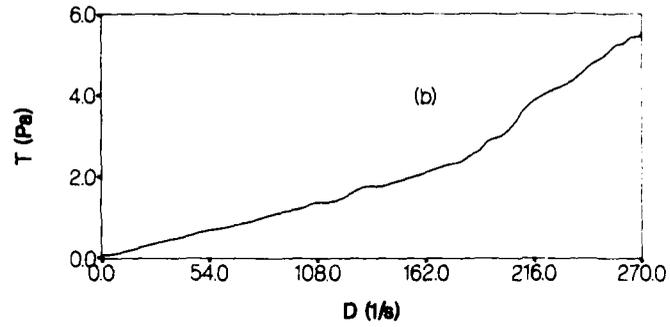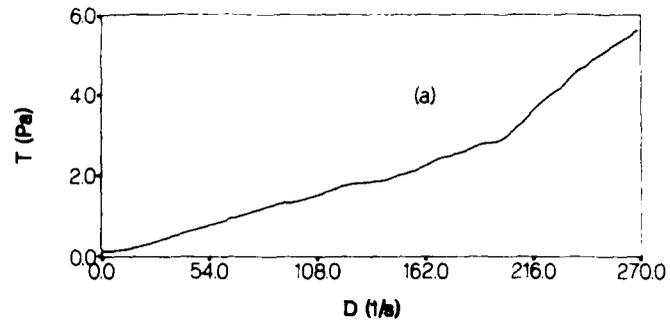
FIGURE 10   Flow curves of commercial grade TNT (exhibiting discontinuity) at (a)
82°C, (b) 85°C and (c) 95°C, using MV II sensor system over a shear rate
range of 0-270 s⁻¹.
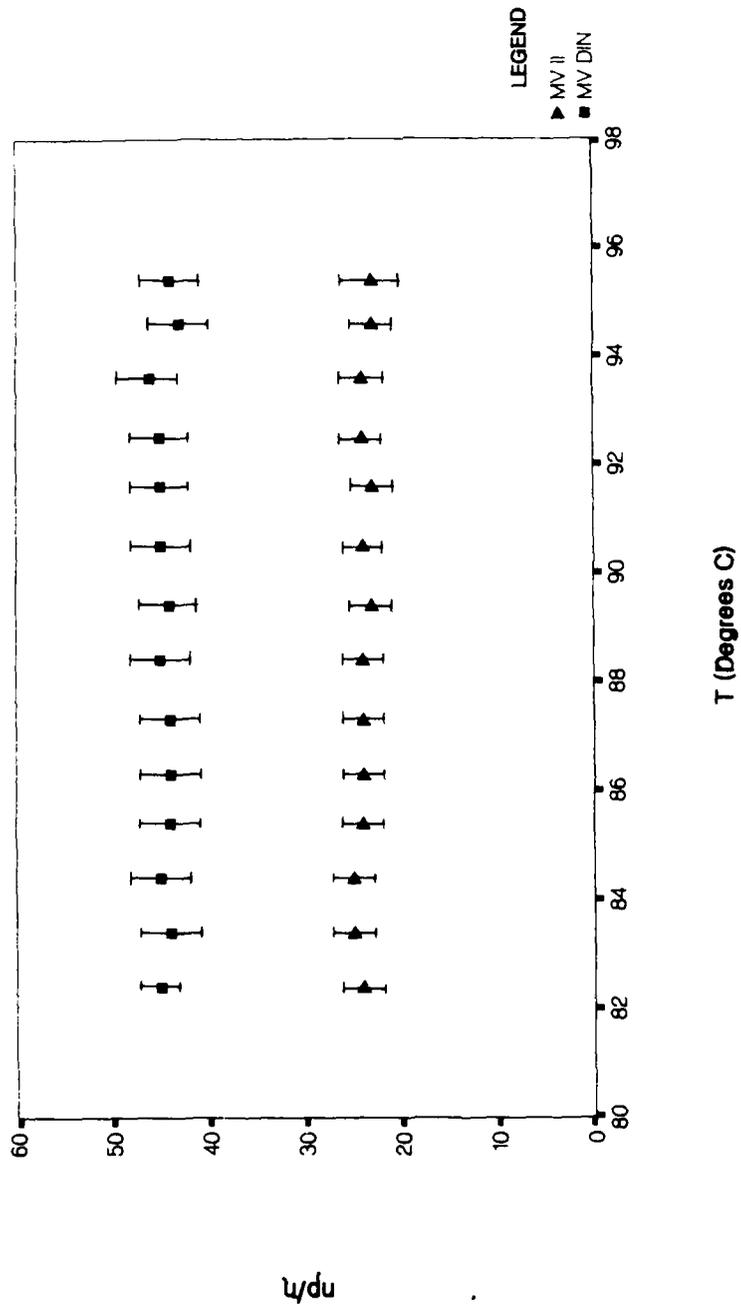
FIGURE 11 Plots of no η versus temperature for commercial grade TNT using MV DIN and MV II sensor systems.

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AUTHOR(S)	CORPORATE AUTHOR
M.A. Parry and H.H. Billon	Materials Research Laboratory PO Box 50, Ascot Vale, Victoria 3032

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ABSTRACT

The flow behaviour of pure and commercial molten TNT, when subjected to very high rates of shear in the temperature range 82.0 to 95.4°C, is presented. All the data obtained suggest that molten TNT is Newtonian, contrary to some published work, and the temperature dependence of the viscosity of pure TNT is adequately described by an Arrhenius-type relationship of the form $\eta = A e^{B/T}$ where $A = 0.000541$, $B = 3570$ and T is the Kelvin temperature. This equation is characteristic of a simple isotropic liquid. A similar relationship is obtained for commercial TNT. Under some instrumental conditions discontinuities are seen in the shear stress - shear rate flow curves. An analysis of these discontinuities shows them to be caused by the transition from laminar to turbulent flow. Possible implications for processibility and initiation of explosives are discussed.

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